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Joe Beasley (PRSO), "Digital Signal Processing Techniques for Positioning of Off-axis Solar Concentrators"

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(Statement A)

Digital Signal Processing Techniques for Positioning of Off-axis Solar Concentrators

Joseph N. Beasley

Abstract:

This paper will discuss the results of using digital signal processing (DSP) techniques to determine the location of the focal point of an off-axis solar concentrator projected onto a visually complex thruster absorber and secondary concentrator. Once the location of the focal spot is located, position control information is generated to move the concentrator to a location that maximizes power transfer. A program that simulates an off-axis solar concentrator is used to generate binary "image" files to analyze for positioning information. The analysis progresses from Discrete Fourier analysis on the two-dimensional images, through spectrograms, to introduce wavelets and wavelet analysis to verify conceptually using DSP techniques to determine position information.

Introduction:

Solar Thermal Propulsion (STP) is a promising concept for use in an Orbital Transport Mission, a deep space mission, or other upper stage space missions requiring high Specific Impulse engines. Since the energy for propulsion is available to the spacecraft in orbit, an STP system would not have to carry propellant and oxidizer to produce energy for the upper stage unit. Only an atomic or molecular propellant such as hydrogen would be needed on the upper stage. The STP system heats up hydrogen in the thruster and then expands the hydrogen through a nozzle to produce the thrust required by the vehicle. Thus the thrust-to-weight efficiency of the STP system is much better (up to two times better) than the equivalent chemical upper stage as less non-payload mass is needed in the STP system for the same amount of thrust to be developed.[i]

A major difference between a chemical-type thruster/spacecraft and an STP thruster/spacecraft is that the STP spacecraft has the added task of controlling the solar concentrators. Not only does the spacecraft need to properly point the concentrators towards the sun while the engine maneuvers in space, it needs to protect them from the exhaust of the spacecraft. These two requirements limit the control region of the concentrators, thus possibly limiting the available power or limiting maneuverability of the spacecraft itself. A final control requirement is that the focal cone should always be positioned on the aperture closest to the nozzle for effective heat transfer to the propellant.[ii]

The current concept for the solar concentrators for a solar thruster is two off axis paraboloid concentrators connected to a central thruster. See Figure 1.

Figure 1: SOLAR-THERMAL SPACECRAFT CONFIGURATION.

Each concentrator is connected to the central thruster with a hexapod unit offering 6 degree of freedom (DOF) control. The 6 DOF needed are yaw, pitch, roll, x, y, and z. Optical analysis for a flight demo concentrator system indicates that the required angular pointing accuracy is 0.1 deg and the translation accuracy should be 0.1 inch. Coarse alignment is obtained using an on axis detector that brings the spacecraft and concentrators into a general alignment with the sun. Coarse alignment brings the focal cone into rough alignment with the desired aperture on the thruster.[iii] Concentrator control should provide optimum energy transfer to the solar thruster

while protecting the concentrator and spacecraft from the dynamic behavior of the whole system.

Focal Spot:

A major requirement for using a solar propulsion system is proper placement of the focal spot on the thruster absorber plane. Without proper placement of the focal spot solar energy is not transferred properly to the propellant gas or at worse case, none of the incident solar energy is transferred to the gas.

The distribution of intensity in the focal spot is modified by the surface it is scattered from, i.e the absorber. The detected intensity is complicated by shadows and the specular component of reflection. Furthermore, at different points in the focal spot, the direction of incident light varies. Therefore, as the focal spot drifts across the absorber the distribution of scattered light changes in a complicated way and it is difficult to determine how to correct pointing. Digital signal processing can be used to "deconvolve" the misaligned focal spot image from the scattering distribution of the thruster absorber. In the case of the current research, the sensors used for focal spot placement consist of a coarse alignment sensor for gross movement of the collectors, followed by fine alignment sensors for precise alignment of the focal spot. Proper alignment is determined by examining the shape, size and intensity of the light of the focal spot on the absorber.

Sensors that allow this type of examination and that would handle the high temperatures presented at the absorber are not readily available. Two possibilities are Charge Coupled Device (CCD) arrays and photo diode detector arrays. The CCD array would be positioned out of direct sunlight, using a lens system for imaging, and would therefore be somewhat protected from the intense heat, the photo diodes would be in direct sunlight and would have to handle the high temperatures.

Based upon these preliminary requirements for fine focus control of the solar concentrator, this paper will utilize a CCD-type of sensor or image as the primary method for the simulation of the focal spot image generated by an off-axis paraboloid concentrator.

Simulation:

A C program called off-axis generatés the focal spot information, based upon having a Lambertian target at the focal plane. This program was written by Dr. Michael R. Holmes of the Air Force Research Laboratory, specifically for inflatable concentrators, and provides an "image" of the focal spot target area being illuminated by an off-axis concentrator. Output data generated by offaxis.c represented the focal spot image intensity. Although, the simulation produces ideal focal beams, using ray-tracing with Monte Carlo slope error simulation, it is an important starting place to prove that the concepts in this paper could work, and supplied important data for analysis to begin. Since the simulation produced a nearly ideal situation, the focal spot generated resulted in a Gaussian-type focal spot intensity distribution. Contour and surface plots of the simulation results are shown in Figures 2-5 indicating the Gaussian 3-dimensional nature of the focal beam.

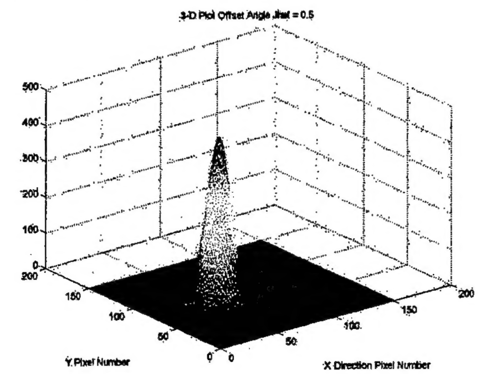

Figure 2: 3-DIMENSIONAL PLOT OF FOCAL SPOT FOR OFFSET JHAT = 0.5

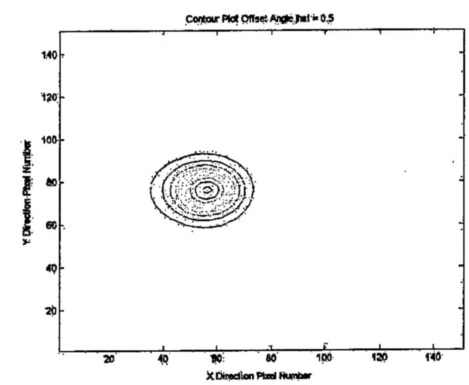

Figure 3: CONTOUR PLOT OF FOCAL SPOT SHOWN IN FIGURE 2.

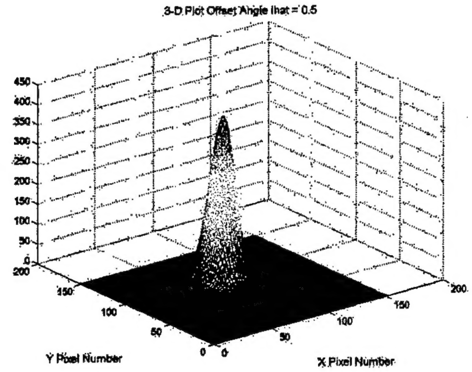

Figure 4: 3-DIMENSIONAL PLOT OF FOCAL SPOT BEAM FOR OFFSET IHAT = 0.5

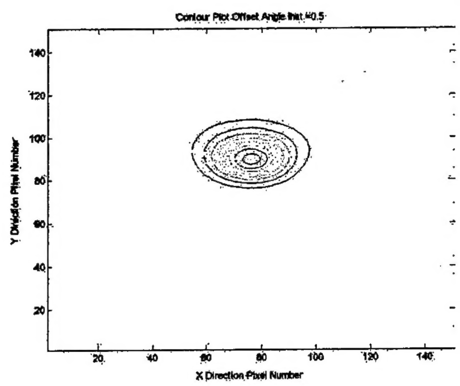

Figure 5: CONTOUR PLOT OF FOCAL SPOT SHOWN IN FIGURE 4.

The contour plot shows that the focus spot is actually elliptical instead of perfectly circular. The elliptical nature of the focus is due to the off axis nature of the concentrator and will be utilized in the determination of the location of the focus. The parameters for the sun and concentrator positions are passed to the program through offaxis.h. By varying the parameters in this file, the various mis-aligned positions of the sun and concentrator can be simulated. Of primary concern to this paper are the sun's offset angle parameters. These two parameters change the angular position of the solar disc in the x, (IHAT) and y, (JHAT) directions. See Figure 6 for the geometry.

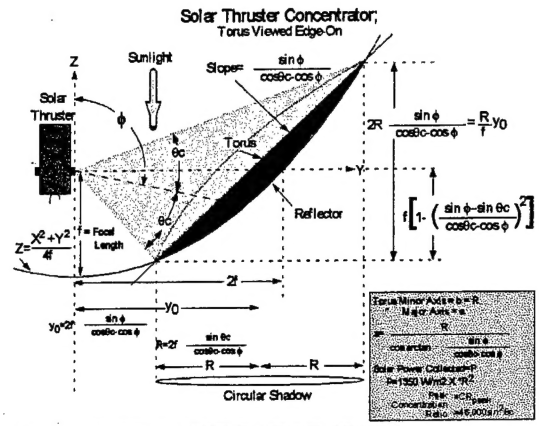

Figure 6: OFF-AXIS PARABOLOID GEOMETRY.

The simulation runs for this paper varied these two parameters only. Note that once the data was generated, the image matrix was treated in an X-Y image data plane instead of what is represented in Figure 6, that is the focal spot data image is presented in its own X-Y plane separate from the coordinate system depicted in Figure 6. One of the issues not addressed in this paper is the conversion of the X-Y focal plane data into concentrator control inputs, to be addressed in a later paper. The specific concentrator modeled in the runs was a 4 X 6 meter Flight Scale Concentrator manufactured by SRS Technologies, Huntsville, AL.

Analysis Methods:

Once the image data were generated, the data were analyzed using Matlab. Initial analysis used the 2-dimensional Fourier Transform (FT) or Fast Fourier Transform (FFT) as Matlab implements this transform. Equation 1 shows the definition of the 2-dimensional continuous Fourier Transform, with the limits of integration being $\pm\infty$.

$$\iint f(x,y)e^{-j(\omega x+vy)}dx\,dy \qquad \text{Eqn. 1}$$

The FFT is a fast mathematical algorithm for computing the discrete form of Equation 1, see Equation 2 for discrete FT, utilized by computers to speed up the calculation of FT's in one dimension. In general cases, the 2-dimensional FFT may be calculated by using the 1-dimensional case and applying it to the data twice.

$$\sum f(n)e^{-j\omega_N nk} \qquad \text{Eqn. 2}$$

with $\omega_N = 2\pi f/N$, and summed over n.

However, this turned out to be futile as the Fourier Transform of a Gaussian shaped signal is also Gaussian. See Figure 7.

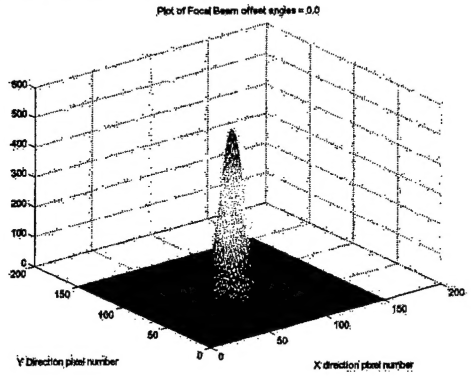

Figure 7: 3-DIMENSIONAL PLOT OF FFT OF FOCAL SPOT BEAM.

Since the transform shape of the beam intensity was identical to the un-transformed shape no position information could be identified using the 2-dimensional Fourier Transform.
The next method of analysis performed was a variant of the Short Time Fourier Transform (STFT) for time signals. The image data was treated as a matrix in Matlab and a vector Fourier Transform (FT) was performed on the matrix. Matlab performs the FFT on a matrix by performing the transform on each column. What this does to the matrix, in effect, is perform a windowed FFT or STFT on the image. See Equation 3, w(t) is the window function in the 1 dimensional continuous transform.

$$\int w(t-\tau)f(t)e^{-j\omega t}dt \qquad \text{Eqn. 3}$$

In fact, the window happens to be rectangular shaped and is exactly one column size in length. The shift value, τ, for each FFT also happened to be one column length, thus making the calculation fairly straightforward to accomplish and actually located at each X value. The result of using the STFT on the image was a 2-dimensional graph depicting the FT of the image in lines along the Y axis on a grid spacing identical to the X axis grid. Thus, the STFT provided a frequency distribution along the Y axis, but local to each X value.
The position of the focal beam was determined by finding the maximum value of the transforms in each direction. These maximums were then used to calculate the amount of correction in each direction needed to re-center the beam.

Another method of determining focal spot location from image data is actually an extension of the STFT called the Wavelet Transform. The Wavelet transform is a multi-resolution transform that takes the 1 dimensional time signal into the scale-time domain, with scale related to frequency (1/f). Thus a wavelet determines the frequency of a signal and also displays the specific time at which that frequency occurs. Although the description of the wavelet sounds exactly like the STFT, they are most definitely two different transforms. The main difference between the wavelet and the STFT is that the STFT uses a fixed grid in transforming the sampled time signal to the frequency domain whereas the wavelet uses a variable grid in both time and frequency[iv]. A variable grid for the wavelet transform allows the user to trade-off frequency resolution and time resolution to provide a better representation of the signal. Another property of the wavelet is its finite bases functions. The bases functions of a wavelet transform are limited to a finite interval over the real line, whereas the Fourier Transform bases functions are infinite cosine and sine waves. The finite qualities of the wavelets make them ideal for representing short duration and transient signals, such as image data, that Fourier transforms have difficulty in representing.

Results:
The results of performing the STFT on various offset angles are shown in Figures 8-13. Comparing the data plots from the STFT's to the contour plots, Figures 14-16 of the same offset angles, gave the sense that STFT's would provide the needed information about the location of the focal spot in the X and Y directions. Table 1 describes each of the graphs.

Table 1

Figure 8	STFT X Dir	IHAT = 0.5 deg.
Figure 9	STFT Y Dir	IHAT = 0.5 deg.
Figure 10	STFT X Dir	JHAT =0.5 deg.
Figure 11	STFT Y Dir	JHAT =0.5 deg.
Figure 12	STFT X Dir	IHAT=JHAT=0.1 deg.
Figure 13	STFT Y Dir	IHAT=JHAT=0.1 deg.
Figure 14	Contour plot	IHAT = 0.5 deg.
Figure 15	Contour plot	JHAT = 0.5 deg.
Figure 16	Contour plot	IHAT=JHAT=0.1 deg.

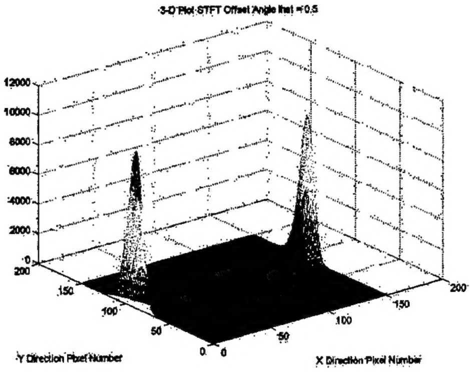

Figure 8: STFT IN X DIRECTION, IHAT =0.5.

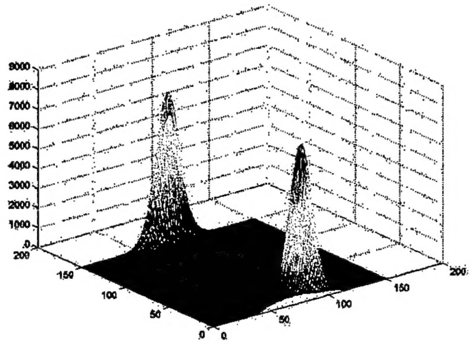

Figure 9: STFT IN Y DIRECTION, IHAT = 0.5.

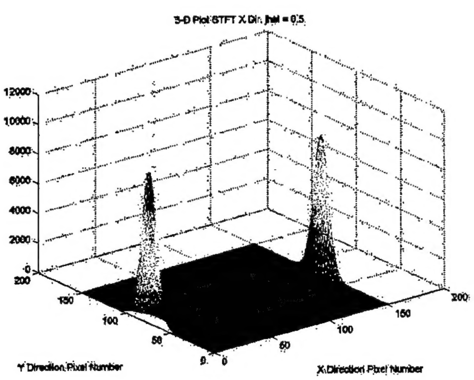

Figure 10: STFT IN X DIRECTION, JHAT = 0.5.

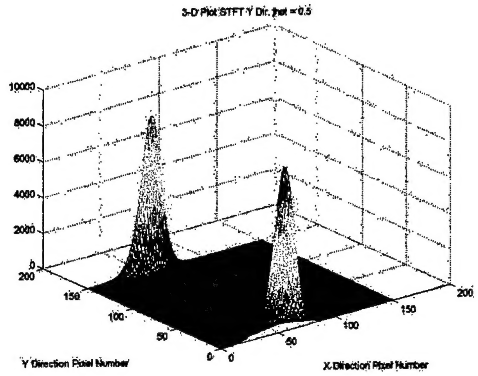

Figure 11: STFT IN Y DIRECTION, JHAT = 0.5.

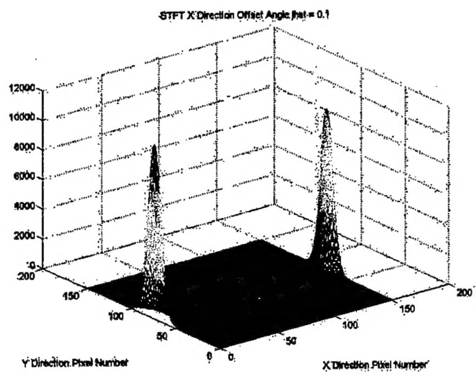

Figure 12: STFT IN X DIRECTION, JHAT = IHAT = 0.1.

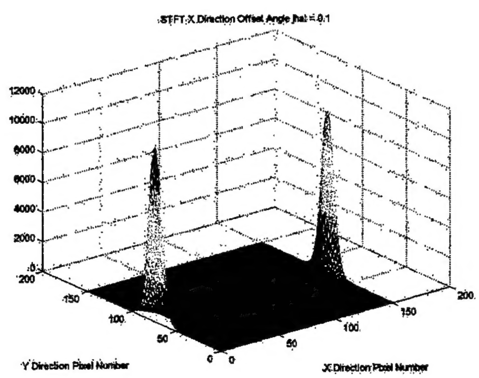

Figure 13: STFT IN Y DIRECTION, JHAT = IHAT = 0.1.

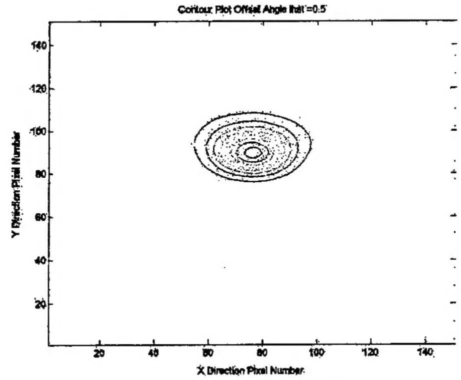

Figure 14: CONTOUR PLOT OF FOCAL SPOT, IHAT = 0.5.

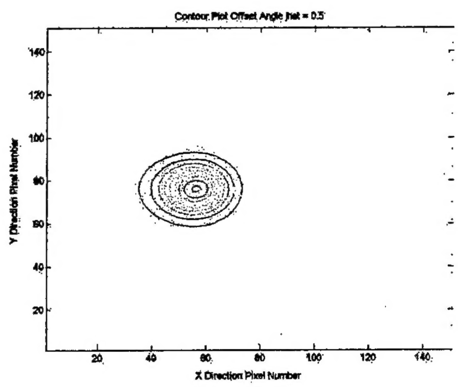

Figure 15: CONTOUR PLOT OF FOCAL SPOT, JHAT = 0.5.

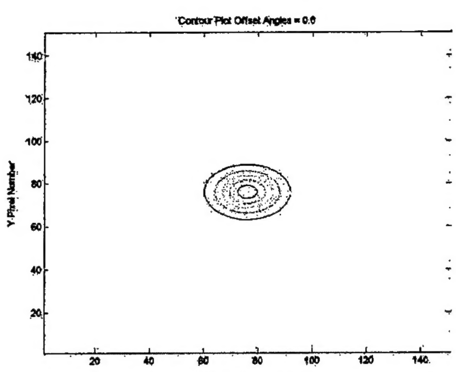

Figure 16: CONTOUR PLOT OF FOCAL SPOT, JHAT = IHAT = 0.1.

Computing the STFT first along the Y direction (columns of the matrix) determined position of the beam in the X direction. Computing the STFT along the X direction (using the transposed matrix) determined the location of the focal beam in the Y direction. Finding the maximum of the spectrum and correlating that to the pixel number of that maximum gave the X, Y location of the focal spot of the focal beam. Table two gives the results of finding maximum values for each of the cases in figures 8-13

Table 2

Figures 8-9	X pixel Number = 76	Y pixel Number = 90
Figures 10-11	X pixel Number = 56	Y pixel Number = 76
Figures 12-13	X pixel Number = 72	Y pixel Number = 76

Each of the pixel numbers in table 2 would be converted to physical measurements using the scaling factors in offaxis.c. The factor in the computer runs presented in this paper is 0.226 units of measurement per pixel. The units in most cases are either centimeters or millimeters.

A problem with the use of the STFT in the situations presented, is that some of the offset angles produced only a change in magnitude and the width of the focal beam and not necessarily a change in its X, Y location. The beam was not expected to change peak frequency value, but it was expected to change position in either X or Y. When the beam expanded or narrowed due to the mis-alignment but did not move the beam in X or Y, the STFT did not provide the necessary position information. The STFT, however, was able to show that the focal beam width and the maximum value of the focal beam had changed, but only when the offset plot was compared to the zero offset plot, visually.

Conclusion:

Data from a computer program was used to generate nearly ideal concentrator performance that was analyzed using the STFT. The results of using the 1 dimensional STFT on images showed promise, thus verifying the concepts, in using the STFT in determining the placement of the focal beam. The STFT's were performed first along the Y axis to determine the pixel number of the maximum beam value in the X direction, then the STFT's were performed along

the X axis to determine the pixel number of the maximum beam value in the Y direction. These results provided incentive to continue analyzing the data using the STFT. One problem that occurred when using the STFT, was that in some instances, the beam only changed in magnitude and not direction. In this case, the STFT does not provide sufficient information to get control information.

Another method was introduced, wavelet analysis was introduced as a method to provide multi-resolution capability, that may or may not resolve the problem in determining when the only change in beam characteristics, was beam intensity. More research will have to be conducted on using wavelets in determining beam positioning.

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[i] Holmes, Dr. Michael R., "Ideal Performance of Off-Axis Paraboloid Concentrators for Solar-Thermal Propulsion," ASME 1996

[ii] IBID

[iii] Wassom, Dr. Steven R., "Focus Control System for Solar Thermal Propulsion," 2000 International ADAMS User Conference.

[iv] Strang, Gilbert, "Wavelet Transforms Versus Fourier Transforms", Bulletin of the American Mathematical Society, Volume 28, Number 2, April 1993.